Cryogenic performances of a heat exchanger prototype suitable for the superconducting HL-LHC recombination dipole D2

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Abstract. In the framework of the future High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, most superconducting magnets in the Long Straight Sections will be replaced. Among them, the new D2 recombination dipole will be a He II conduction-cooled magnet with a larger aperture than the LHC dipoles. To provide the required cooling (up to 70 W) to the D2 and to comply with its cryostat integration constraints, a compact heat exchanger was designed by the CEA Département des Systèmes Basses Températures (DSBT) based on a CERN preliminary analysis and a CEA review of the possible cooling schemes. This heat exchanger provides the required heat transfer between the He II pressurized bath and the He II saturated bath to cool the D2 magnet in different operating conditions at 1.8 K and 2 K. The detailed design of the heat exchanger was defined and one prototype was manufactured by industry under the CEA supervision. The heat exchanger prototype is composed of roughly one hundred oxygen-free high purity copper tubes, electron beam welded to the stainless steel He II bath enclosure. The present paper describes the successful cryogenic performance tests of the prototype of the D2 heat exchanger measured in the CEA 400W@1.8K test facility in Grenoble.

1. Introduction

Current and next generations of large particle accelerators or colliders as well as thermonuclear fusion reactors, nuclear magnetic resonance magnets or high field magnets use superconducting conductors and/or superconducting accelerating cavities. Superfluid helium cooling offers the possibility to improve the performance of such superconducting devices with lower operating temperatures and provides extremely high heat extraction capacities.

Among all the equipment already in operation with He II, the largest one is the Large Hadron Collider (LHC) at CERN with thousands of superconducting magnets working around 1.9 K [1]. In its upgraded version, the High Luminosity Upgrade of the LHC (HL-LHC) will provide instantaneous luminosities up to five times larger than the LHC nominal value. To do so, most of the existing LHC superconducting magnets in two of the interaction points will be replaced, including the D2 recombination dipole magnets. This implies that this new D2 dipole and its cooling system, including the pressurized He II / saturated He II heat exchanger, must be compatible with the existing tunnel constraints. In particular, the heat exchanger must be very compact.

Due to the very high heat conduction of He II, the D2 magnet will be cooled by conduction in static pressurized He II. Indeed, convection will not improve the overall cooling as the heat transfer between a wall and He II is largely limited by the thermal resistance at the interface (the so-called Kapitza resistance), which is independent of the relative fluid/wall velocity. These two effects militate in favor of dimensioning a He II/He II heat exchanger using only the conduction of the fluid [2][3][4].

The detailed design of the heat exchanger was defined by CEA in collaboration with CERN and one heat exchanger prototype was manufactured by industry under the CEA supervision. The heat exchanger prototype, as illustrated in figure 1, is composed of roughly one hundred oxygen-free high purity copper tubes (OFE copper tubes- 500 mm long, 10 mm internal diameter and 1 mm thick), electron beam welded to stainless steel flanges in the He II bath enclosure. The present paper describes the successful cryogenic performance tests of the D2 heat exchanger prototype measured in the CEA 400W@1.8K test facility at Grenoble [5].

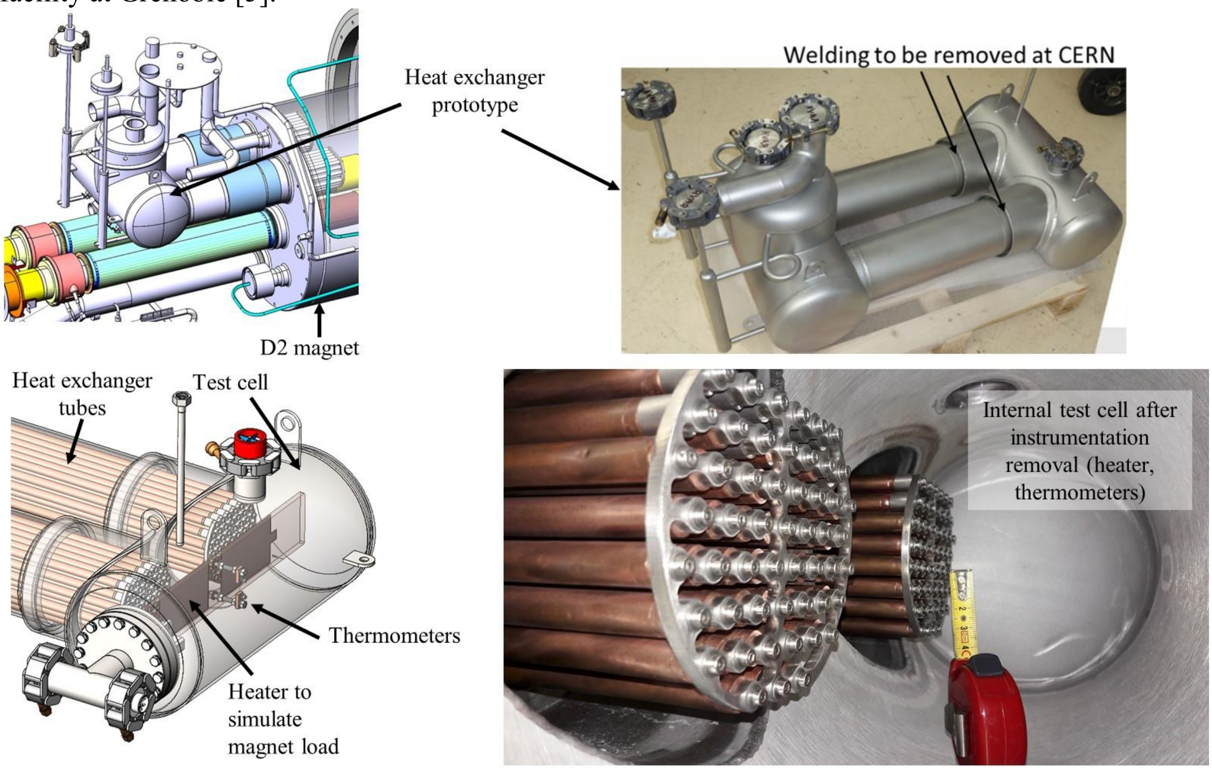

Figure 1. Heat exchanger overview (from left to right and top to bottom): installation in D2 magnet cryostat, prototype picture, test cell details, prototype copper tubes internal view in the test cell.

2. Description of the test facility and the associated instrumentation

After manufacturing and the complete factory controls (liquid nitrogen thermal cycles of each copper tube after electron beam welding, followed by individual pressure and He leak tightness tests before final tube assembly and overall tests), the D2 heat exchanger prototype was installed and tested in the test facility 400W@1.8K.

This test facility consists of a Helium refrigerator and a large Multi-Test Cryostat. The cooling capacity of the He refrigerator is greater than 100 W from 4.2 K to 1.5 K. For the present HL-LHC component testing, the Multi-Test Cryostat has been modified to install the heat exchanger prototype with its test cell and a set of cryogenic valves and dedicated instrumentation (temperature, pressure, liquid level, electrical heaters). The Process Flow Diagram (PFD) of the heat exchanger prototype (HX-D2) installed in the cryostat is shown in figure 2.

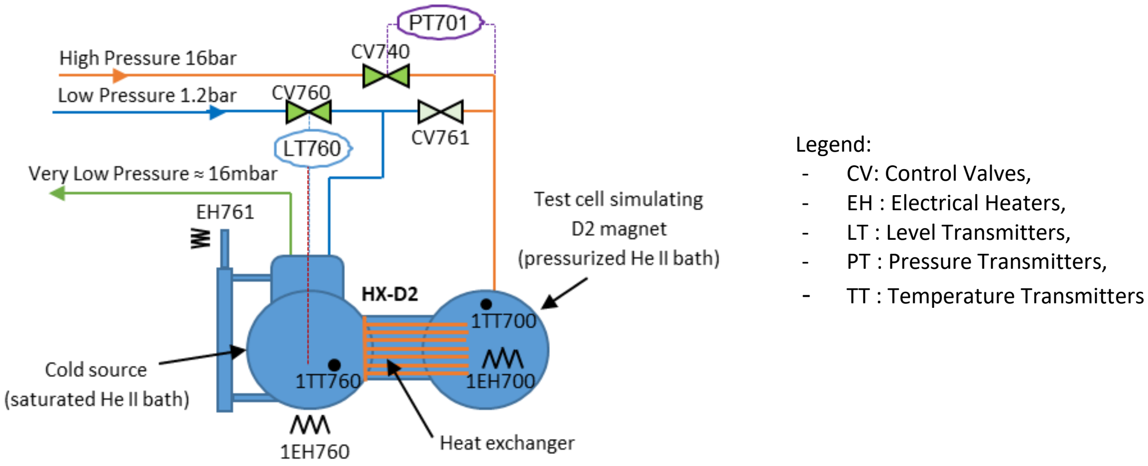

Figure 2. Process Flow Diagram (PFD) of the HX-D2 heat exchanger prototype installed in the 400W@1.8K test facility.

The assessment of the heat exchanger cooling performance is performed by measuring the temperature difference across the heat exchanger as a function of the heating power applied in the test cell. This corresponds to measuring the temperature difference between the pressurized He II and saturated He II baths. A temperature gradient is likely to occur within the pressurized He II bath along the magnet. Both heating power and temperature are applied and measured in the test cell simulating the D2 magnet in the final real configuration. The corresponding instruments are the heater 1EH700 and the temperature sensors 1TT700 and 1TT760 in figure 2.

To simulate the future D2 magnet operation in the HL-LHC, the heat exchanger prototype and its test cell were installed with a slope of +1.4% corresponding to the worst case of the LHC tunnel configuration. During operation, the quasi-horizontal tubes of the heat exchanger must be completely wet and immersed to a sufficient depth to avoid any risk of film boiling in the He II saturated bath. This is ensured by measuring and controlling the liquid helium level with superconducting level gauges.

For reasons of redundancy, each sensor is doubled. Two thermometers and two heaters were installed in the pressurized He II part of the heat exchanger in the test cell as well as two thermometers and two level gauges in the saturated He II bath. The thermometers as well as the heaters are connected by four wires and are immersed in the liquid He II to allow accurate measurements. Pressure sensors are connected through capillary tubes to the two heat exchanger baths.

In addition, heaters are installed on the He II saturated bath enclosure of the heat exchanger, allowing the adjustment of the heating power injected in the He II pressurized bath while maintaining a constant evaporated mass flow in the sub-atmospheric pumping line (i.e. a constant total heating power), so maintaining the same cryogenic conditions in the cold compressors and the cold end of the He refrigerator.

3. Cryogenic performance requirements for the compact heat exchanger

The nominal operation for the D2 magnets are specified with 50 W heat loads along the magnet, 1.3 bar in the He II pressurized bath and a cold source regulated at 1.8 K. Following previous calculations on the allowed thermal gradient along the D2 magnet itself [2], the thermal performance requirements of the HX-D2 heat exchanger have been defined for the following three cryogenic operating points with two degraded conditions among the three nominal ones:

1) **Quasi-nominal operation point** (nominal pumping in the return very low-pressure line resulting in **1.8 K** cold source and leaking Supercritical helium (SHe) supply valves in D2 magnets resulting in a higher pressure of **4 bar** in the pressurized helium and higher heat loads of **70 W** along the magnet): the temperature difference between the He II pressurized part and the liquid-vapour interface should not exceed **220 mK.**

2) **Degraded operation point** (additional pressure drop in the return very low pressure pumping line resulting in **2 K** cold source, nominal **1.3 bar** pressure in D2 magnet and higher heat loads of **70 W** along the magnet): the temperature difference between the pressurized part and the liquid-vapour interface should not exceed **54 mK**.
3) **Ultimate operation point** (additional pressure drop in the return very low-pressure pumping line resulting in **2 K** cold source, and leaking SHe supply valves in D2 magnets resulting in a higher pressure of **4 bar** in the pressurized helium and nominal **50 W** heat loads along the magnet): the temperature difference between the pressurized part and the liquid-vapour interface should not exceed **55 mK**.

To be sure not only to fulfil these thermal performance requirements but also to validate the proposed model of the superfluid helium cooling scheme [4] and to evaluate the remaining design and operation margins, a larger parameters domain was explored. The influence of the injected heating power was therefore studied from 0 W to 115 W.

4. Temperature measurement control

During cooldown and warmup, crossing the lambda line can be identified and used as a verification of the calibration of the thermometers. Thus, at the beginning of the warmup, the sub-atmospheric operation is stopped. The discharge valve of the He II pressurized part of the heat exchanger (CV761 in figure 2) is opened to equilibrate the pressure of the two baths. This procedure allows to obtain two saturated stratified baths, with liquid vapour interface at 4.2 K/1.05 bar, and a vertical thermal gradient down to $T\lambda$ in the liquid. Due to the very efficient heat conductivity of He II, almost all the liquid (where thermometers are located) remains quasi isothermal at a temperature just below $T\lambda$ (like the so-called "Roubeau bath").

The predicted value of temperature at $T\lambda$ and 1.05 bar is 2.167 K according to Hepak [6] while the thermometers in the tested heat exchanger indicate 2.163 K as shown in figure 3. This small difference (less than 5 mK for absolute temperature) may be due to calibration accuracy. Remarkably identical value is found on thermometers at both sides of the heat exchanger. This provides a very good confidence in temperature difference measurements around 2 K recorded during the HX-D2 performance tests.

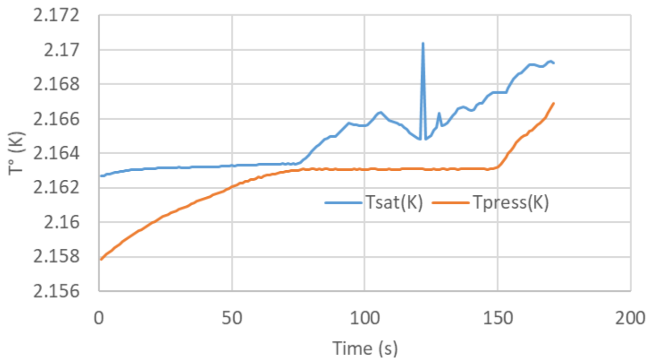

Figure 3. Crossing the $T\lambda$ line during warm-up, the pressure kept at 1.05 bar in both He baths

5. Heat exchanger performance and analysis

Raw data measurements of the temperature difference between the two He II baths are presented in **Figure 4.** for different injected heating powers. In all cases, the liquid level above the heat exchanger tubes is regulated and sufficient to operate the heat exchanger correctly. The temperature indicated in the legend corresponds to the temperature of the He II saturated bath and the pressure in the He II pressurized bath, while the y-axis indicates the measured temperature difference between the end of the He II pressurized bath in the test cell and the He II saturated bath of the heat exchanger.

Without injected heating power, it is remarkable to see very small temperature differences (2.2 mK at 1.8 K and 4.3 bar, 1.1 mK at 2 K and 1.3 bar and 0.7 mK at 2 K and 4 bar respectively), which confirm the good accuracy of the thermometers. A part (or all) of this difference can be attributed to static heat losses. These small values also confirm low heat losses.

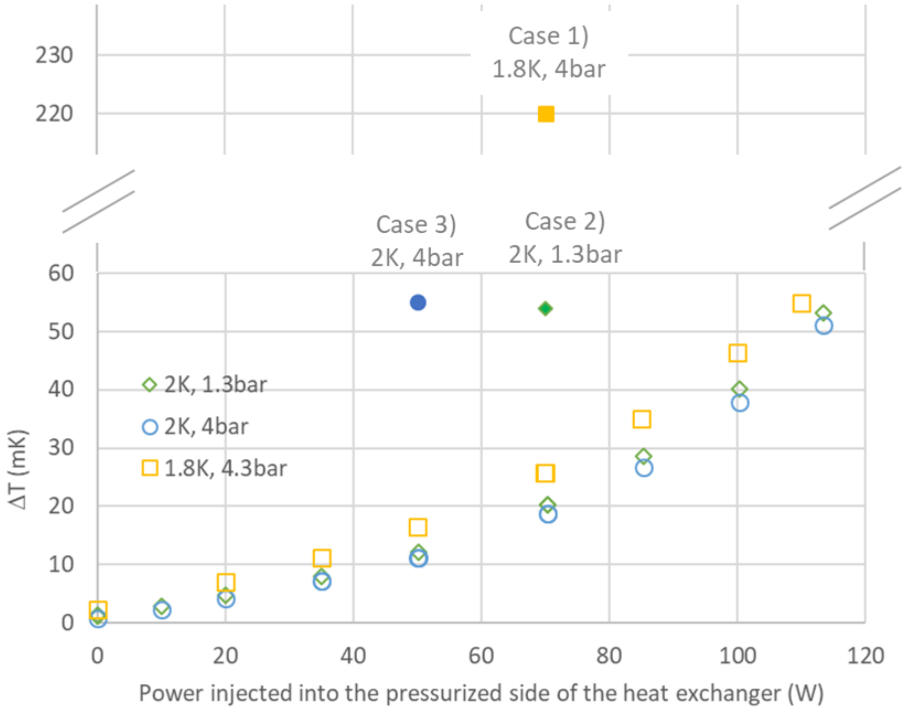

Figure 4. Raw data showing the temperature difference between the He II pressurized and saturated sides of the heat exchanger prototype at different operating temperatures and pressures.

In all tests with heating, the ΔT across the heat exchanger remains always lower than the thermal requirements specified in the operation case n°2 (54 mK at 2 K, 1.3 bar and 70 W) and stays lower than 50 mK up to 100 W of injected heating power.

One can observe that the ΔT is slightly larger for 1.8 K tests than for 2 K ones, which can be attributed to the lower transverse thermal conductivity at the lower temperature (both the thermal conductivity of copper and the conductance of Kapitza decrease at low temperatures). The non-linear shape of all ΔT = f(P) curves may be surprising: in most cases, when heat transfer between He II and a heated surface is involved, the relation between temperature difference and heat flux is linear for small temperature differences. The observed non-linear behavior cannot be attributed to the Kapitza resistance because the power law would have exactly the opposite result.

In fact, this non-linear behavior is due to the increase in heat flux $\dot{Q}$, which generates a ΔT in the He II liquid with a power law with an exponent of 3.4 [7]. In our optimized compact He II/He II heat exchanger, the ΔTs along the tubes and in the channels between tubes are not negligible. For a perfect optimum as explained in [4] and shown in figure 5, this longitudinal ΔT should be equal to the transverse ΔT at the nominal heat flux.

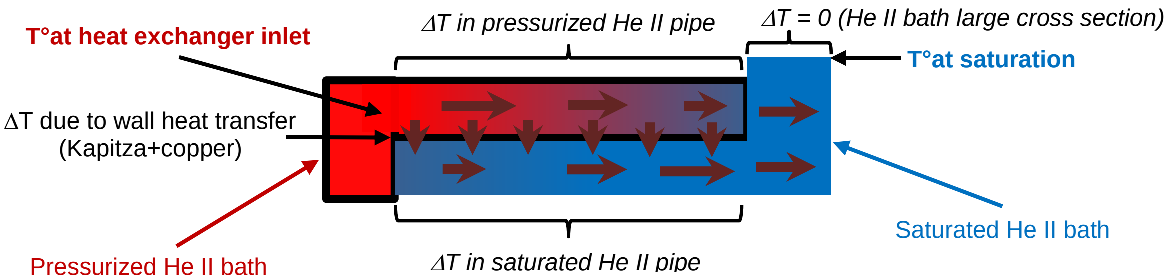

Figure 5. Heat transfer and temperature profiles in one heat exchanger sector

For low heat flux, the ΔT due to transverse thermal resistance is preponderant and the behavior of ΔT = f($\dot{Q}$) remains almost linear for these small ΔT. But unlike other non-optimized He II/He II heat exchangers, at larger heat flux the longitudinal ΔT is an important contribution, and the curve ΔT = f($\dot{Q}$) exhibits a power law with an exponent larger than one.

Because of this non-linear behavior, the static heat losses effect cannot be compensated by a simple offset of the temperature difference corresponding to its initial value with heat losses only. It is therefore of primary importance to accurately estimate the static heat losses when their contributions are not negligible. The estimation of the static heat losses as well as additional tests of the heat exchanger are described in a companion paper presented at this conference [8].

Another remark that arises from the measurements concerns the influence of pressure: surprisingly, the heat transfer seems to improve at 2 K when the pressure increases from 1.3 to 4 bar. However, even if this heat transfer increase is not understood, it remains very low and within the limits of the overall accuracy of the sensors.

6. Conclusion

The present paper reports the cryogenic performance tests of the compact He II-He II heat exchanger prototype for the future high luminosity LHC recombination dipoles D2. The tests were performed in the 400W@1.8K test facility at CEA Grenoble.

The selected design with horizontal tubes filled with saturated He II and penetrating inside the extremity of the D2 cold mass vessel filled with pressurized He II provides an efficient and compact solution offering significant operating margins. Indeed, the measured temperature differences in the heat exchanger prototype with 70 W injected heating power are lower than 20 mK at 2 K and lower than 25 mK at 1.8 K, far below the specified thermal requirements of respectively 54 mK and 220 mK.

The design of the D2 heat exchanger is consequently validated and the fabrication of the required heat exchangers for the HL-LHC project is now in progress.

7. References

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